United States Environmental Protection Agency | Office of Research and Development | Office of Solid Waste and Emergency Response | EPA/540/S-92/003 February 1992

Ground Water Issue

In-Situ Bioremediation of Contaminated Ground Water

J.L. Sims[a], J.M. Suflita[b], and H.H. Russell[c]

An emerging technology for the remediation of ground water is the use of microorganisms to degrade contaminants which are present in aquifer materials. Understanding the processes which drive *in-situ* bioremediation, as well as the effectiveness and efficiency of the utilization of these systems, are issues which have been identified by the Regional Superfund Ground Water Forum as concerns of Superfund decision makers. The Forum is a group of ground-water scientists and engineers, representing EPA's Regional Superfund Offices, organized to exchange up-to-date information related to ground-water remediation at Superfund sites.

Although *in-situ* bioremediation has been used for a number of years in the restoration of ground water contaminated by petroleum hydrocarbons, it has only been in recent years that this technology has been directed toward other classes of contaminants. Research has contributed greatly to understanding the biotic, chemical, and hydrologic parameters which contribute to or restrict the application of *in-situ* bioremediation, and has been successful at a number of locations in demonstrating its effectiveness at field scale.

This document is one in a series of *Ground Water Issue* papers which have been prepared in response to needs expressed by the Ground Water Forum. It is based on findings from the research community in concert with experience gained at sites undergoing remediation. The intent of the document is to provide an overview of the factors involved in *in-situ* bioremediation, outline the types of information required in the application of such systems, and point out the advantages and limitations of this technology.

For further information contact Dr. Hugh Russell, RSKERL, FTS 743-2444, commercial number (405) 332-8800.

Summary

In-situ bioremediation, where applicable, appears to be a potential cost-effective and environmentally acceptable remediation technology. Suflita (1989) identified characteristics of the ideal candidate site for successful implementation of *in-situ* bioremediation. These characteristics included: (1) a homogeneous and permeable aquifer; (2) a contaminant originating from a single source; (3) a low ground-water gradient; (4) no free product; (5) no soil contamination; and (6) an easily degraded, extracted, or immobilized contaminant. Obviously, few sites meet these characteristics. However, development of information concerning site specific geological and microbiological characteristics of the aquifer, combined with knowledge concerning potential chemical, physical, and biochemical fate of the wastes present, can be used to develop a bioremediation strategy for a less-than-ideal site.

Introduction

In-situ bioremediation is a technology to restore aquifers contaminated with organic compounds. Organic contaminants found in aquifers can be dissolved in water, attached to the aquifer material, or as freephase or residual phase liquids referred to as NAPLs which are liquids that do not readily dissolve in water (Palmer and Johnson, 1989c). Generally,

[a] ***Soil Scientist, Utah Water Research Laboratory, Utah State University***
[b] ***Professor, Dept. of Botany and Microbiology, University of Oklahoma***
[c] ***Research Microbiologist, Robert S. Kerr Environmental Research Laboratory***

Superfund Technology Support Center for Ground Water

Robert S. Kerr Environmental Research Laboratory
Ada, Oklahoma

Technology Innovation Office
Office of Solid Waste and Emergency Response, US EPA, Washington, DC

Walter W. Kovalick, Jr., Ph.D.
Director

monitoring wells (Devitt et al., 1988; Palmer and Johnson, 1989b).

The distribution of the source area and the extent of contamination should also be characterized by collecting cores of the solid aquifer materials. Precise information is required to define the vertical extent of contamination so that nutrients, oxygen and other amendments injected into the aquifer contact the contaminants. Injection into a clean part of the aquifer is a wasted effort and may give the false impression that the region of aquifer between the injection and recovery wells is clean (Figure 3).

Additional characteristics of waste contaminants present at a specific site that should be considered are related to their environmental fate and behavior in specific aquifer materials (Armstrong, 1987; Johnson et al., 1989). These characteristics include physical and chemical properties that determine recalcitrance, reactivity, and mobility of contaminants at the site. Information concerning partitioning of contaminants between aquifer solids and water is especially important. This information is used to evaluate the extent and rate of release of contaminants into the ground water, their mobility, and the quantity of electron acceptors and inorganic nutrients that must be supplied to support *in-situ* bioremediation.

Aquifer Characterization

Important geological characteristics of an aquifer that should be considered during a site investigation include the composition and heterogeneity of aquifer material, specific yield, hydraulic connections to other aquifers, magnitude of water table fluctuations, ground-water flow rate and direction, hydraulic conductivity distribution, permeability, bulk density, and porosity (Lee et al., 1988; Palmer and Johnson, 1989a).

Hydraulic conductivity (K) is an especially important characteristic since the aquifer must be permeable enough to allow the transport of electron acceptors and inorganic nutrients to the microorganisms in the zone of contamination. Permeable aquifer systems, i.e., aquifers with K values of 10^{-4} cm/sec or greater, are usually considered good candidates for *in-situ* bioremediation (Thomas and Ward, 1989).

Hydraulic conductivity of an aquifer can be determined by a variety of methods (Thomas et al., 1987b, Palmer and Johnson, 1989a). Knowledge of K values at multiple locations is necessary because of the heterogeneity of aquifer materials. Laboratory methods are also available for determining hydraulic conductivity, but field-measured values represent average properties over a larger volume and utilize less disturbed materials (Palmer and Johnson, 1989a).

Aquifer characteristics play an extremely important role in determining the effectiveness of *in-situ* bioremediation. Even in the presence of organisms acclimated to the specific waste constituents present in an aquifer, biodegradation of contaminants may be limited by unfavorable aquifer characteristics that affect microbial activity including:

1. insufficient concentrations of dissolved oxygen for aerobic metabolism of compounds susceptible to aerobic degradation;
2. excessive oxygen that inhibits anaerobic biodegradation of many halogenated compounds in the subsurface;

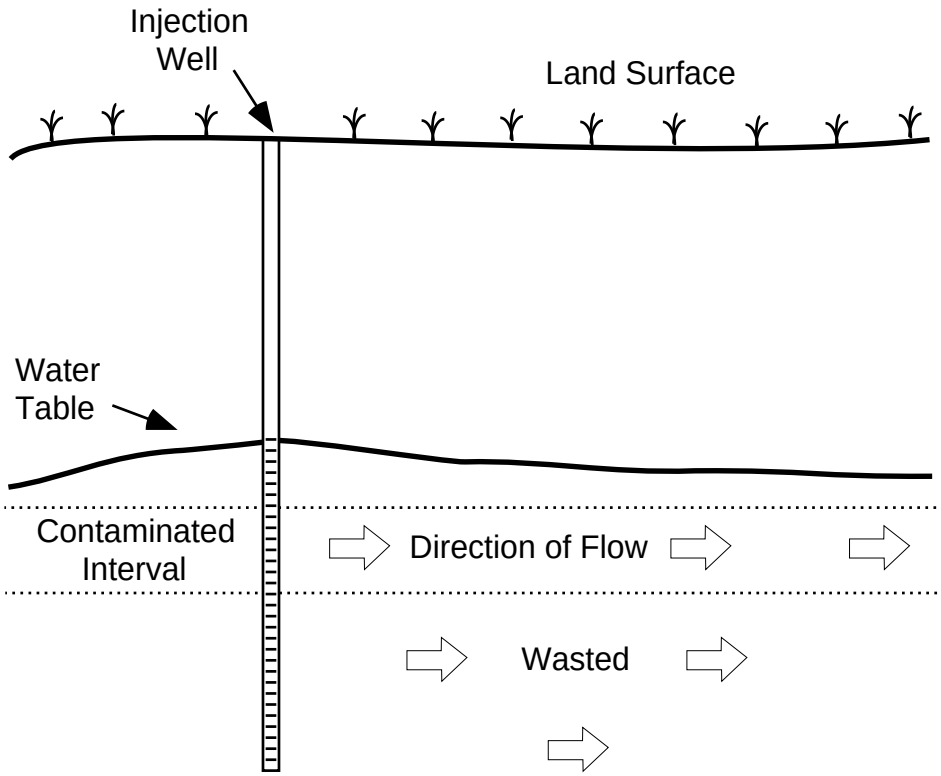

Figure 3. The value of accurately locating the contaminated interval (Wilson et al., 1989).

3. lack of a suitable alternative electron acceptor, if oxygen is unavailable or not usable;
4. insufficient inorganic nutrients, such as nitrogen, phosphorus, and trace minerals;
5. presence of toxic metals or other toxicants; and
6. other aquifer characteristics, such as pH, buffering capacity, salinity, osmotic or hydrostatic pressures, radiation, sorptive capacity, and temperature (Armstrong, 1987; Lee et al., 1988).

Treatability Study

A treatability study is designed to determine if bioremediation is possible at a specific site, and whether there are any biological barriers to attaining clean-up goals. Even though the scientific literature may indicate that a specific chemical is likely to biodegrade in the environment, a treatability study using site specific variables should be used to confirm that contention (Suflita, 1989a). Microcosms are generally used to conduct treatability studies. Pritchard (1981) defined a microcosm as "a calibrated laboratory simulation of a portion of a natural environment in which environmental components, in as undisturbed a condition as possible, are enclosed within definable physical and chemical boundaries and studied under a set of laboratory conditions." Microcosms may range from simple batch incubation systems to large and complex flow-through devices (Suflita, 1989a).

Results of a treatability study can also provide an estimate of the rate and extent of remediation that can be attained if microorganisms are not limited by the rate of supply of an essential growth factor or by the presence of an unfavorable environmental factor.

Treatability studies to determine inorganic nutrient and electron acceptor requirements of subsurface microorganisms present at a specific site should be conducted using samples of subsurface solids as well as the ground water. Nutrient and electron acceptor requirements that will enable indigenous microorganisms to efficiently degrade organic contaminants present at a specific site can be determined by incubating contaminated subsurface materials with combinations of levels of inorganic nutrients and electron acceptors. Studies should be performed under conditions that simulate field environmental conditions. Results of the studies are used to design the bioremediation program as well as to optimize the treatment strategy.

Design and Implementation of an *In-Situ* Bioremediation System

Before implementation of an *in-situ* bioremediation system, the source of contamination in the soil and in the ground water should be removed as much as possible. In the case of a liquid fuel spill, source removal may consist of recovery of LNAPL free product from the ground water. Depending on the characteristics of the aquifer and contaminants, free product can account for as much as 91 percent of the spilled hydrocarbon, with the remaining hydrocarbon (accounting for 9-40 percent of the spill) sorbed to the soil or dissolved in the ground water (Lee et al., 1986).

Physical recovery techniques, based on the fact that LNAPL hydrocarbons are relatively insoluble in and less dense than water, are used to remove free product from a contaminated site. Physical recovery often accounts for only 30 to 60 percent of spilled hydrocarbon before yields decline. Continued pumping of recovery wells may be used to contain a spill while *in-situ* bioremediation is being implemented. If a spill is comprised of DNAPLs, which may sink to the bottom of the aquifer, physical recovery may be considerably more difficult to achieve.

Information from the performance of site characterization and treatability studies may be integrated with the use of comprehensive mathematical modeling to estimate the expected rates and extent of treatment at the field scale (Javandel, 1984; Keely, 1987). The specific model chosen should incorporate biological reaction rates, stoichiometry of waste transformation, mass-transport considerations, and spatial variability in treatment efficiency (U.S. EPA, 1989a).

After assessment of site characterization and treatability studies, if results indicate that *in-situ* bioremediation is applicable to the site and will be an effective clean-up technology, the information collected is used to design and implement the system.

When *in-situ* bioremediation of a contaminant ground-water plume involves using methods to enhance the process, such as the addition of nutrients, additional oxygen sources, or other electron acceptors, the use of hydraulic controls to minimize migration of the plume during the *in-situ* treatment process may be required (Thomas et al., 1987c; U.S. EPA, 1989a). In general, hydraulic control systems are generally less costly and time consuming to install than physical containment structures such as slurry walls. Well systems are also more flexible, for pumping rates and well locations can be altered as the system is operated over a period of time.

Pumping-injection systems can be used to: (1) create stagnation zones at precise locations in a flow field; (2) create gradient barriers to pollution migration; (3) control the trajectory of a contaminant plume; and (4) intercept the trajectory of a contaminant plume (Shafer, 1984). The choice of a hydraulic control method depends on geological characteristics, variability of aquifer hydraulic conductivities, background velocities, and sustainable pumping rates (Lee et al. 1988). Typical patterns of wells that are used to provide hydraulic controls include: (1) a pair of injection-production wells; (2) a line of downgradient pumping wells; (3) a pattern of injection-production wells around the boundary of a plume; and (4) the "double-cell" hydraulic containment system. The "double-cell" system utilizes an inner cell and an outer recirculation cell, with four cells along a line bisecting the plume in the direction of flow (Wilson, 1984).

Well systems also serve as injection points for addition of the materials used for enhancement of microbial activity and for control of circulation through the contaminated zone. The system usually includes injection and production wells and equipment for the addition and mixing of the nutrients (Lee et al., 1988). A typical system in which microbial nutrients are mixed with ground water and circulated through the contaminated portion of the aquifer through a series of injection and recovery wells is illustrated in Figure 4 (Raymond et al., 1978; Thomas and Ward, 1989).

Materials can also be introduced to the aquifer through the use of infiltration galleries (Figure 5) (Brenoel and Brown,

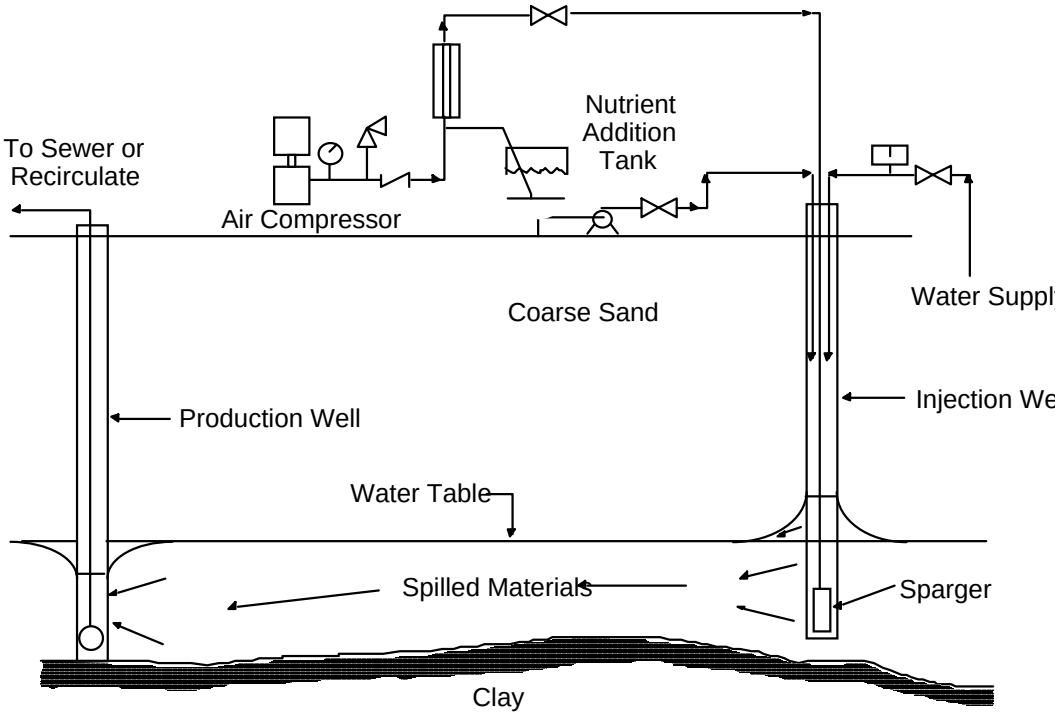

Figure 4. Typical schematic for aerobic subsurface bioremediation (Thomas and Ward, 1989).

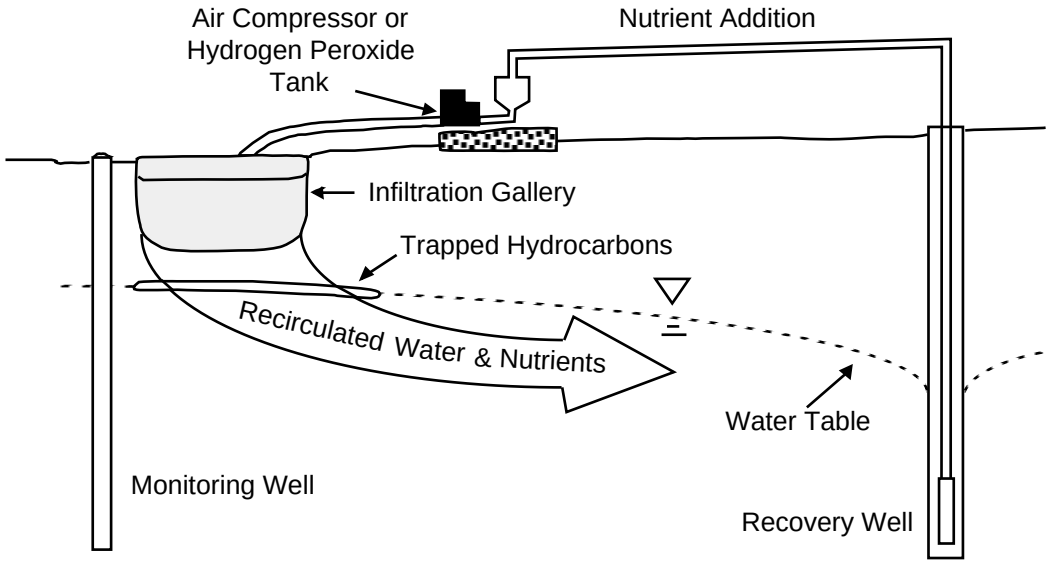

Figure 5. Use of infiltration gallery for recirculation of water and nutrients in in-situ bioremediation (Thomas and Ward, 1989).

1985; Thomas and Ward, 1989). Infiltration galleries allow movement of the injection solution through the unsaturated zone as well as the saturated zone, resulting in potential treatment of source materials that may be trapped in the pore spaces of the unsaturated zone.

Amendments to the aquifer are added to the contaminated aquifer in alternating pulses. Inorganic nutrients are usually added first through the injection system, followed by the oxygen source. Simultaneous addition of the two may result in excessive microbial growth close to the point of injection and consequent plugging of the aquifer. High concentrations of hydrogen peroxide (greater than 10%) can be used to remove biofouling and restore the efficiency of the system.

Operations Monitoring

Both the operation and effectiveness of the system should be monitored (Lee et al., 1988). Operational factors of importance include the delivery of inorganic nutrients and electron acceptor, the point of the delivery within the aquifer in relation to the contaminated portion of the plume, and the effectiveness of containment and control of the contaminated plume.

Measurements of dissolved oxygen and nutrient levels in ground-water samples are recommended to assess whether or not bioremediation is being accomplished. Increases in microbial activities in samples of aquifer materials may be quantified relative to plume areas prior to treatment, areas within the plume that did not receive treatment, and control areas outside the plume. Carbon dioxide levels in ground-water samples may also be a useful indicator of microbial activity (Suflita, 1989b).

Measurement of contaminant levels should indicate that concentrations of contaminants are decreasing in areas receiving treatment and remaining relatively unchanged in areas that are not. If degradation pathways of specific contaminants are known, measurement of presence and concentrations of metabolic products may be used to determine whether or not bioremediation is occurring. Both soil and ground-water samples should be collected and analyzed to develop a thorough evaluation of treatment effectiveness. The use of appropriate control samples, e.g., assays of untreated areas or areas outside the plume, is highly recommended to confirm the effectiveness of the bioremediation technology (Suflita, 1989b).

The frequency of sampling should be related to the time expected for significant changes to occur along the most contaminated flow path (U.S. EPA, 1989a). Important considerations include time required for water to move from injection wells to monitoring wells, seasonal variations in water table elevation or hydraulic gradient, changes in the concentration of dissolved oxygen or alternative electron acceptor, and costs of monitoring.

Advantages and Limitations in the Use of *In-Situ* Bioremediation

There are a number of advantages and disadvantages in the use of *in-situ* bioremediation (Lee et al., 1988). Unlike other aquifer remediation technologies, it can often be used to treat contaminants that are sorbed to aquifer materials or trapped in pore spaces. In addition to treatment of the saturated zone, organic contaminants held in the unsaturated and capillary zones can be treated when an infiltration gallery is used.

The time required to treat subsurface pollution using *in-situ* bioremediation can often be faster than withdrawal and treatment processes. A gasoline spill was remediated in 18 months using *in-situ* bioremediation, while pump-and-treat techniques were estimated to require 100 years to reduce the concentrations of gasoline to potable water levels (Raymond et al., 1986). *In-situ* bioremediation often costs less than other remedial options. The areal zone of treatment using bioremediation can be larger than with other remedial technologies because the treatment moves with the plume and can reach areas that would otherwise be inaccessible.

There are also disadvantages to *in-situ* bioremediation programs (Lee et al., 1988). Many organic compounds in the subsurface are resistant to degradation. *In-situ* bioremediation usually requires an acclimated population of microorganisms which may not develop for recent spills or for recalcitrant compounds. Heavy metals and toxic concentrations of organic compounds may inhibit activity of indigenous microorganisms. Injection wells may become clogged from profuse microbial growth resulting from the addition of nutrients and oxygen.

In-situ bioremediation is difficult to implement in low-permeability aquifers that do not permit the transport of adequate supplies of nutrients or oxygen to active microbial populations. In addition, bioremediation projects require continuous monitoring and maintenance for successful treatment.

References

Aelion, C. M., C. M. Swindoll, and F. K. Pfaender. 1987. Adaptation to and Biodegradation of Xenobiotic Compounds by Microbial Communities from a Pristine Aquifer. Appl. Environ. Microbiol. 53:2212-2217.

Acker, W. L., III. 1974. Basic Procedures for Soil Sampling and Core Drilling. Acker Drill Co. Scranton, PA.

Armstrong, J. 1987. Some Problems in the Engineering of Groundwater Cleanup. p. 110-120. In: N. Dee, W. F. McTernan, and E. Kaplan (eds.) Detection, Control, and Renovation of Contaminated Ground Water. Am. Soc. Civil Eng., New York, NY.

Barcelona, M.J. and J.A. Helfrich. 1986. Well Construction and Purging Effects on Ground-Water Samples. Environ. Sci. Technol. 20:1179-1184.

Barcelona, M.J., J.P. Gibb, J.A. Helfrich, and E.E. Garske. 1985. Practical Guide for Ground-Water Sampling. EPA/600/2-85/104, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Brenoel, M., and R.A. Brown. 1985. Remediation of a Leaking Underground Storage Tank with Enhanced Bioreclamation. Proc., Fifth National Symp. on Aquifer Restoration and Ground Water Monitoring. National Water Well Assoc., Worthington, OH.

Canter, L.W., and R.C. Knox. 1985. Ground Water Pollution Control. Lewis Publishers, Chelsea, MI.

Devitt, D.A., R.B. Evans, W.A. Jury, T.H. Starks, B. Eklund, A. Ghalsan. 1988. Soil Gas Sensing for Detection and Mapping of Volatile Organics. EPA/600/8-87/036, Environmental Monitoring and Support Laboratory, U.S. Environmental Protection Agency, Las Vegas, NV.

Dunlap, W.J. and J.F. McNabb. 1973. Subsurface Biological Activity in Relation to Ground Water Pollution. EPA-660/2-73-014, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Dunlap, W.J., J.F. McNabb, M.R. Scalf, and R.L. Cosby. 1977. Sampling for Organic Chemicals and Microorganisms in the Subsurface. EPA-600/2-77-176, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Ehrenfield, J. and J. Bass. 1984. Evaluation of Remedial Action Unit Operations of Hazardous Waste Disposal Sites. Pollution Technology Review No. 110, Noyes Publications, Park Ridge, NJ.

Ford, P.J., P.J. Turina, and D.E. Seely. 1984. Characterization of Hazardous Waste Sites - A Methods Manual, Volume II: Available Sampling Methods. EPA/600/4-84/076. Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Ghiorse, W.C., and D.L. Balkwill. 1985. Microbiology of Ground Water Environments. In: G. E. Januer (ed.) Progress in Chemical Disinfection II: Problems at the Frontier. State Univ. of New York (SUNY) at Binghamton, Binghamton, NY.

Ghiorse, W.C., and J.T. Wilson. 1988. Microbial Ecology of the Terrestrial Subsurface. Adv. Appl. Microbiol. 33:107-172.

Goldstein, R.M., L.M. Mallory, and M. Alexander. 1985. Reasons for Possible Failure of Inoculation to Enhance Biodegradation. Appl. Environ. Microbiol. 50:977-983.

Javandel, I., C. Doughty, and C.F. Tsang. 1984. Groundwater Transport: Handbook of Mathematical Models. Water Resources Monograph No. 10, Am. Geophysical Union, Washington, DC.

Johnson, R.L., C.D. Palmer, and W. Fish. 1989. Subsurface Chemical Processes. In: Transport and Fate of Contaminants in the Subsurface. EPA/625/4-89/019, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Keely, J.F. 1987. The Use of Models in Managing Ground-Water Protection Programs. EPA/600/8-87/003. Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Keely, J.F. and K. Boateng. 1987. Monitoring Well Installation, Purging, and Sampling Techniques. Part II: Case Histories. Ground Water 25:427-439.

Kilbane, J.J. 1986. Genetic Aspects of Toxic Chemical Degradation. Microbiol. Ecol. 12:135-145.

Leach, L.E., F.P. Beck, J.T. Wilson, and D.H. Kampbell. 1988. Aseptic Subsurface Sampling Techniques for Hollow-Stem Auger Drilling. Proc., Second National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods 1:31-51.

Lee, M.D. and C.H. Ward. 1986. Ground Water Restoration. Report submitted to JACA Corporation, Fort Washington, PA.

Lee, M.D., J.M. Thomas, R.C. Borden, P.B. Bedient, J.T. Wilson, and C. H. Ward. 1988. Biorestoration of Aquifers Contaminated with Organic Compounds. CRC Critical Rev. Environ. Controls 18:29-89.

McNabb, J.F., and G.E. Mallard. 1984. Microbiological Sampling in the Assessment of Groundwater Pollution. In: G. Bitton and C.P. Gerba (eds.), Groundwater Pollution Microbiology. John Wiley & Sons, New York, NY.

Palmer, C.D., and R.L. Johnson. 1989a. Determination of Physical Transport Parameters. In: Transport and Fate of Contaminants in the Subsurface. EPA/625/4-89/019, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Palmer, C.D., and R.L. Johnson. 1989b. Physical Processes Controlling the Transport of Contaminants in the Aqueous Phase. In: Transport and Fate of Contaminants in the Subsurface. EPA/625/4-89/019, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Palmer, C.D., and R.L. Johnson. 1989c. Physical Processes Controlling the Transport of Non-Aqueous Phase Liquids in the Subsurface. In: Transport and Fate of Contaminants in the Subsurface. EPA/625/4-89/019, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Pritchard, P.H. 1981. Model Ecosystems. In: R.A. Conway (ed.), Environmental Risk Analysis for Chemicals. Van Nostrand Reinhold, New York, NY.

Raymond, R.L. 1974. Reclamation of Hydrocarbon Contaminated Ground Waters. U.S. Patent Office, Washington, DC. Patent No. 3,846,290. Patented November 5, 1974.

Raymond, R.L., R.A. Brown, R.D. Norris, and E.T. O'Neill. 1986. Stimulation of Biooxidation Processes in Subterranean Formations. U.S. Patent Office, Washington, DC. Patent No. 4,588,506. Patented May 13, 1986.

Raymond, R.L., V.W. Jamison, J.O. Hudson, R.E. Mitchell, and V.E. Farmer. 1978. Field Application of Subsurface Biodegradation of Gasoline in a Sand Formation. API Publication 4430, American Petroleum Institute, Washington, DC.

Scalf, M.R., J.F. McNabb, W.J. Dunlap, R.L. Cosby, and J. Fryberger. 1981. Manual of Ground Water Sampling Procedures. National Water Well Assoc., Worthington, OH.

Schafer, J.M. 1984. Determining Optimum Pumping Rates for Creation of Hydraulic Barriers to Ground Water Pollutant Migration. In: D.M. Nielsen (ed.), Proc., Fourth National Symp.

on Aquifer Restoration and Ground Water Monitoring. National Water Well Assoc., Worthington, OH.

Stolzenburg, T.R. and D.G. Nichols. 1985. Preliminary Results on Chemical Changes in Groundwater Samples Due to Sampling Devices. EPRI Report No. EA-4118, Electric Power Research Institute, Palo Alto, CA.

Suflita, J.M. 1989a. Microbial Ecology and Pollutant Biodegradation in Subsurface Ecosystems. In: Transport and Fate of Contaminants in the Subsurface. EPA/625/4-89/019, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Suflita, J.M. 1988b. Microbiological Principles Influencing the Biorestoration of Aquifers. In: Transport and Fate of Contaminants in the Subsurface. EPA/625/4-89/019, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Thomas, J.M., and C.H. Ward. 1989. In Situ Biorestoration of Organic Contaminants in the Subsurface. Environ. Sci. Technol. 23:760-766.

Thomas, J.M., M.D. Lee, and C.H. Ward. 1987a. Use of Ground Water in Assessment of Biodegradation Potential in the Subsurface. Environ. Toxicol. Chem. 6:607-61 4.

Thomas, J.M., H.J. Marlow, R.L. Raymond, and C.H. Ward. 1987b. Hydrologic Considerations for In Situ Biorestoration. US/USSR Symposium on Fate of Pesticides and Chemicals in the Environment, Oct. 12-16, Iowa City, IA (under review by John Wiley & Sons, Inc., New York, NY).

Thomas, J.M., M.D. Lee, P.B. Bedient, R.C. Borden, L.W. Canter, and C.H. Ward. 1987c. Leaking Underground Storage Tanks: Remediation with Emphasis on In Situ Biorestoration. EPA/600/2-87/008, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

U.S. Environmental Protection Agency. 1989a. Bioremediation of Hazardous Waste Sites Workshop: Speaker Slide Copies and Supporting Information. CERI-89-11, Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, OH.

Wilson, J.L. 1984. Double-cell Hydraulic Containment of Pollutant Plumes. In: D. M. Nielsen (ed.), Proc., Fourth National Symp. on Aquifer Restoration and Ground Water Monitoring. National Water Well Assoc., Worthington, OH.

Wilson, J.T., and B.H. Wilson. 1985. Biotransformation of Trichloroethylene in Soil. Appl. Environ. Microbiol. 49:242-243.

Wilson, J.T. and C.H. Ward. 1987. Opportunities for Bioreclamation of Aquifers Contaminated with Petroleum Hydrocarbons. Dev. Industrial Microbiol. (J. Industrial Microbiol. Suppl. 1) 27:109-116.

Wilson J., L. Leach, J. Michalowski, S. Vandegrift, and R. Callaway. 1989. In Situ Bioremediation of Spills from Underground Storage Tanks: New Approaches for Site Characterization, Project Design, and Evaluation of Performance. EPA/600/2-89/042, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.

Wilson, J.T., J.F. McNabb, D.L. Balkwill, and W.C. Ghiorse. 1983. Enumeration and Characterization of Bacteria Indigenous to a Shallow Water-Table Aquifer. Ground Water 21:134-142.

Wilson, J.T., L.E. Leach, M.J. Henson, and J.N. Jones. 1986. In Situ Biorestoration as a Ground Water Remediation Technique. Ground Water Monitoring Rev. 6:56-64.

Zapico, M.M., S. Vales, and J.A. Cherry. 1987. A Wireline Piston Core Barrel for Sampling Cohesionless Sand and Gravel Below the Water Table. Ground Water Monitoring Rev. 7(3):74-82.